Innovative Farming Methods for Production and Harvest of Manila Clams in Washington State, USA

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The Manila clam *Venerupis philippinarum* (synonymous with *Tapes semidecussata*, *T. philippinarium*, and *T. japonicas*) is a significant aquaculture crop in China, Japan, France and Italy and other shellfish farming regions. Manila clams were accidentally introduced during the 1920s and 1930s to the Pacific coast of North America in oyster seed shipments from Japan. The clam quickly naturalized and spread to become common from southern British Columbia to northern California. It is now an important commercial clam species on the Pacific coast, with nearly all harvest from Washington State, USA (4,300 t in 2015) and British Columbia, Canada.

FIGURE 1. *Samish Bay, North Puget Sound, with the location circled of the Chuckanut Shellfish farm location (left). Layout of the farm showing the locations and lengths of individual planted rows (right). Source: National Geographic Society (left) and Google Earth satellite photo 7-14-2014 (right).*

FIGURE 2. *The Chuckanut Shellfish farm is located in the middle of Samish Bay and several miles from the nearest land. A landing craft is used to access the growing beds and to carry a small tractor, bed maintenance equipment and people across the bay. The day begins and ends with the fall and rise of the tide and at high tide water six feet deep or greater covers the farm.*

While historically much of the production resulted from natural recruitment and limited husbandry, extensive and intensive aquaculture production methods are currently employed in many locations. Most are grown in sand or mixed gravel/sand/shell sediments with or without a protective groundcover of predator netting and harvested manually using short-handled rakes. These labor-intensive husbandry and harvest methods require a large work force and account for 15 to 25 percent of the total production cost of market-sized clams.

About 15 years ago, Chuckanut Shellfish in Samish Bay (Washington State, USA), which is an embayment of Puget Sound, in the Salish Sea (Figs. 1 and 2), began experiments to adapt land-based agricultural practices to Manila clam production, applying results from several years of small-scale trial clam plantings and a long history of successful oyster production in adjacent areas of Samish Bay. The production method combined predator netting, mechanical net deployment and sweeping, and a modified tulip-bulb harvester to intensively cultivate and harvest Manila clams. This has allowed effective predator protection, biofouling control, and efficient harvest. With a per-person harvest rate of 1,100 to 1,300 kg/h, total harvest costs are now reduced to 3 to 5 percent of the farm gate value.

In this article, we describe various aspects of bivalve cultivation and harvest studied at the Chuckanut Shellfish farm. Specific objectives were to assess aspects of planting bed preparation, predator net maintenance and clam harvest with respect to water quality, macroalgae, benthic communities, and mobile macrofauna; and to examine and contrast benthic and epibenthic speciation and abundance between manually and mechanically harvested clams, swept and non-swept predator nets, and farmed or non-farmed substrata. Details of changes in benthic and epibenthic fauna and other site-specific farm site and harvest effects were described in a recent thesis paper (Kralj 2017). In a companion paper, we assessed yield in terms of clam growth, mortality and quality and incorporated the results into a Farm Aquaculture Resource Management (FARM) model to simulate potential harvest, sustainable carrying capacity, and positive and negative aspects of production (Saurel *et al*. 2014). This article focuses on general

(Continued on page 50)

FIGURE 3. *A work barge towed by the landing craft and used to carry the mechanical harvest machine, clam bins, netting and other supplies.*

FIGURE 4. *Installation of predator netting. Clam netting is spooled out from the tractor in long generally north to south rows. Tension is maintained on the net to ensure it lies close to the ground and the edges are driven into the sediment and sealed with planting tools mounted on the tractor. Large metal staples are pushed into the bottom along the length of the netted rows at approximately 50-ft intervals. Once sufficient netting is installed, seed clams are dropped onto the net surface during an incoming tide. These clams drop through the netting and remain in place, covered by the predator net until harvest.*

aspects of farm production and harvest operations.

The principal elements of Chuckanut farm production practice are:

1) Seeding clams in meter-wide rows to facilitate mechanization,
2) Culture in a sand substrate versus a mixed sand-gravel,
3) Mechanized installation of predator nets using a tractor and a modified terrestrial agriculture implement,
4) Using a tractor-mounted street sweeper to clean predator nets,
5) Mechanized net removal and rolling for storage,
6) Mechanized clam harvesting using a modified tulip bulb harvester, and
7) Vessel-assisted retrieval of harvested clams unitized on pallets.

FIGURE 5. *Regular net maintenance is a critical part of clam farm operations. During late spring to early fall, a variety of macroalgae settle and grow on the surface of the net. Much of this algae consists of the green sea lettuce (*Ulva*), along with the brown algae* Fucus *and* Sargassum.

Production Methods at Chuckanut Shellfish Farm

Chuckanut farm is located on a 2.6-ha, intertidal, gently sloping tidal flat isolated from the adjoining shoreline by several deeper channels and broad tidal flats (Fig. 1). The bottom elevation ranges from -0.3 m to 0.0 m Mean Lower Low Water. It has a mixed fine to medium sand substrate and very flat topography. Approximately 70 percent of the area is used for Manila clam culture and the remaining 30 percent forms aisles between cultivated rows. The surrounding bottom has a slightly lower elevation with a light to moderate cover of seagrass (*Zostera marina* and *Zostera japonica)* mixed with the green algae *Ulva* spp. and scattered patches of non-vegetated substrate.

The site is accessed by boat from a staging area located about 4 km west of the farm. Usually a small outboard engine-powered landing craft is used to transport personnel, a work tractor and other farm equipment (Fig. 2). This vessel also tows a barge or scow holding the harvest machine, spools of plastic mesh, and packing supplies (Fig. 3). Typically, two to five workers conduct farm operations during the period of tidal exposure.

FIGURE 6. *A modified tractor-powered "street sweeper" to remove macroalgae biofouling from predator nets.*

FIGURE 7. *A tulip-bulb harvester modified to harvest Manila clams after predator netting has been removed.*

FIGURE 8 (TOP) AND 9 (BOTTOM). *Close-up of the mechanical harvester and clams. A combination of a vibrating rake and rotating brush dig clams buried 2-4 inches deep onto a conveyor. The vibratory action also shakes most of the sand off the clams, so by the time they reach the bins, they are fairly clean. Each bin holds about 50 pounds of clams.*

Reusable polypropylene mesh (6 or 10 mm square openings) predator nets (90-460 m long × 1.2 m wide) are installed in strips, buried along the edges and fixed to the sediment with large steel staples (Fig. 4). Clam seed (3.2-3.5 mm shell length) is planted through the net mesh within strips at about 750 individuals per m^2. During a growing cycle of 2-3 years, nets are swept approximately monthly from spring to fall (net fouling is minimal in winter) to remove fouling (Fig. 5). Fouling occurs mainly through attachment and growth of macroalgae (*Ulva* sp. and *Sargassum* sp.) on predator nets. Before clams grow too large to fit through the mesh, biofouling can result in clams moving to the surface on top of the net but under the algae in an attempt to escape apparent suffocation, but this results in seed loss when nets are swept. Thus, it is critical to keep predator nets clean until clams are too large to move through the mesh. When clams are too large to pass through the predator net, sweeping is necessary to remove macroalgae to avoid suffocation of clams and improve water flow (Fig. 6). Additional farm maintenance involves inspecting and re-burying edges of the predator net. The principal predators excluded are Dungeness crab (*Metacarcinus magister* (formerly *Cancer magister*), the red rock crab (*Cancer productus*), and the graceful crab (*Cancer gracilis*). Surf scoters (*Melanitta perspicillata*) and white-winged scoters (*M. fusca*) are also seasonally important predators (Lewis *et al*. 2007). In the Pacific Northwest, Manila clams are rarely found in significant densities in sand, presumably because they are easily detected and consumed by predators. This was painfully evident to Chuckanut Shellfish as they pioneered farming Manila clams in sand. When nets are dislodged by storms, predation can be 100 percent in as soon as 24 hours.

Clams are harvested during accessible low tides between early spring and late fall, with some harvests continuing through the winter. After removing the predator net, the harvest machine is driven to the end of a harvest row. Harvest proceeds by driving the machine along the length of the harvest row, with the harvest crew picking out broken clams, other bivalves and shell fragments, and filling and palletizing packing bins (Figs. 7-9). During harvest, the machine loosens or softens the upper 8-10 cm of substrate and exposes scattered polychaete worms and smaller clams. However, after the following tidal inundation, the softened layer compacts to a consistency similar to adjacent undisturbed substrate.

(CONTINUED ON PAGE 52)

Environmental Sampling/Monitoring

We completed two seasons (spring-summer 2011-2012) of environmental sampling and monitoring to gather data on water quality and physical changes associated with farm operations. This consisted of 1) placement of YSI 6600 water quality sondes 10 cm off the bottom at the center of the farm and at an adjacent seagrass reference location; 2) deployment of a current meter[1] at the center of the farm to record water movements just above the sediment; 3) placement of Onset temperature data loggers at the northern end of the farm; 4) collection of discrete surface water samples for nutrients, chlorophyll *a*, particulate organic carbon (POC), total nitrogen (TN), and total suspended solids (TSS) analyses; 5) collection of macroalgae from the surfaces of unswept nets; 6) quadrant sampling to determine Manila clam densities and size ranges; 7) benthic infauna sampling from mechanically and manually harvested tracts and from an off-farm reference site; 8) epibenthic sampling from swept and unswept nets, and from sand and seagrass covered reference sites; and 9) fixed video observations of the harvested tracts, open and netted (unharvested) and seagrass habitats. All sampling was coordinated closely with farm operations and included an evaluation of mechanical harvest and an assessment of comparative manual harvests with traditional short-handled rakes. This information was also used in farm-scale modeling efforts described in Saurel *et al*. (2015).

Water Quality

Tidal current velocities at the center and edge of the farm were generally moderate and reached 25 cm/sec during peak tidal flow. Outgoing tides flowed to the north (350°) while incoming tides flowed to the south (170°). Velocities fell to 0 cm/sec at slack tide.

Average water temperature ranged from 13.5 to 16.7 C. Exposure of the farm during low tide events resulted in short-term peaks to nearly 30 C. There was little difference in pH and dissolved oxygen concentrations (2011 data) between the center of the farm and an adjacent unfarmed seagrass bed. Peak pH and dissolved oxygen values coincided with peak tidal velocities (25 cm/sec), regardless of water flow direction. Dissolved oxygen and pH also generally increased during the day from photosynthesis by phytoplankton and macroalgae.

Water quality findings from multiple discrete samples taken on four sampling dates in 2011 are shown in Table 1. All samples were collected during an ebb tide as water left shallow intertidal flats and moved offshore across the length of the farm.

- There was no consistent pattern of chlorophyll, dissolved carbon and nitrogen as water passed through the farm. Chlorophyll ranged from 1.5 to 5.8 µg/L, generally within the range of surface waters in other areas of north Puget Sound (www.ecy.wa.gov). There was a modest increase of carbon as summer progressed into fall, linked to increased TSS.
- TSS concentrations did not decrease or decrease consistently in the late spring and early summer inside the clam farm as compared to water entering the site from the adjacent tide flat. However, there was a marked increase in TSS in the late summer and fall in water entering and exiting the farm, apparently the result of seasonal deterioration of *Ulva* and other macroalgae and of *Zostera marina* in the bay.
- There were strong seasonal trends in nutrients, with the exception of phosphate. There were no consistent differences between sample sites for phosphate, silicate, and nitrite+nitrate. Silicate levels fell in the late summer and fall at each sample site, likely reflecting a decline in diatoms relative to other phytoplankton taxa. Levels of ammonium increased during the same period, exceeding levels reported during late spring and early summer.

Water quality changes as tidal water flowed across the farm site were modest and seen in changed TSS and ammonium. Oxygen, carbon dioxide, ammonium, reactive silica and phosphorus fluxes in Sacca di Goro, an intensively cultivated lagoon in Italy, were stimulated several fold from respiration and excretion by clams (Bartoli *et al*. 2001). In this clam farm, oxygen consumption was 3 to 4 times and ammonium efflux was 1.9 to 4.9 times greater than those measured in a control site, with rates positively correlated with clam biomass (Nizzoli *et al*. 2007). Mesocosm and field studies suggest that bivalves are a major contributor of ammonium to intertidal water (Bendell *et al*. 2014). We observed an increase and a decrease in ammonium values in the water column within or adjacent to Chuckanut farm. Ammonium appeared to be driven by levels in water entering the farm from adjacent tide flats and not the increased presence of Manila clams.

Biofouling

Increased late spring to summer biofouling on predator nets by macroalgae (Table 2) can be attributed to increased bay temperatures and elevated ammonium concentrations at the sediment-water interface. FARM model results from the Chuckanut farm (Saurel *et al*. 2015) indicate that ammonium excretion by clams is a nutrient source for macroalgae. Further, planted rows with larger second and third year clams had greater seaweed biomass peaks. Higher density and larger clams have the potential to drive benthic metabolism in farmed areas and to sustain macroalgal growth through regeneration of inorganic N (Nizzoli *et al*. 2007).

The physical presence of predator nets also provides favorable habitat for macroalgae colonization, which would normally be less likely to successfully colonize open sand sediment. The total biomass was substantial, calculated at 17.5 t wet weight in June 2011 and close to 29 t in early May of 2012 before intensive net sweeping (Table 2). By October of both years it was reduced to 2 to 3 t because of the combined effects of sweeping, decreased temperatures and decreased sunlight. Currently, swept seaweeds float away or decompose in the areas between clam rows, but Chuckanut is working on potential uses of swept macroalgae.

Aquatic Life Around Chuckanut Farm

The Chuckanut farm harbors a diverse assemblage of animals and plants living with and adjacent to clams, growing on predator nets, and swimming over the farm. These organisms were the objects of an intensive multi-season sampling effort addressing four principal areas: 1) harvest method: differences in benthic or in-sediment samples before and after harvest on mechanically and manually harvested plots; 2) overall farm effect: benthic samples from farmed plots compared to non-farmed plots; 3) net sweeping effect: epibenthic invertebrates from two different unfarmed seagrass and sand substrates compared with swept and non-swept predator nets; and 4) fixed video observations of fish and macrofauna at harvest, netted and reference sites.

TABLE 2. Results of analyses of seasonal water sampling for chlorophyll, particulate organic carbon, total suspended solids, phosphate, silicate, nitrate and ammonium, at the NW (outgoing) and SE (incoming), and center of the farm in 2011. All samples were taken during an ebbing or falling tide (shoreward margin) shortly before the farm tract was exposed.

Sample Date and Location	*[Chl] µg/l*	*[POC] mg/l*	*[TN] mg/l*	*[TSS] mg/l*	*[PO4-P] µg/l*	*[SiO_4-Si] µg/l*	*[NO_{3+2}-N] µg/l*	*[NH_4-N] µg/l*
Late Spring (May)								
Outgoing	3.7	0.9	0.14	7.2	51	1,775	7.5	11
Center	3.9	0.9	0.13	7.8	54	1,746	13.7	10
Incoming	5.1	1.1	0.15	7.7	53	1,737	12.2	15
Mid-Summer (July)								
Outgoing	5.8	1.3	0.18	4.3	39	1,272	2.1	10
Center	4.3	0.9	0.13	4.7	40	1,299	1.3	13
Incoming	4.7	1.0	0.15	3.8	42	1,326	0.8	12
Late Summer (August)								
Outgoing	2.4	0.7	0.08	19.8	34	816	2.6	30
Center	2.5	0.6	0.08	10.9	38	855	2.5	16
Incoming	2.7	0.6	0.07	13.5	42	895	3.1	25
Early Fall (October)								
Outgoing	4.1	0.6	0.08	16.7	43	567	32.7	25
Center	1.4	0.6	0.07	10.9	41	574	34.0	32
Incoming	1.5	1.5	0.19	13.5	34	634	22.6	17

TABLE 3. Estimated total wet and dry weight of macroalgae (*Ulva, Sargassum*, etc.) colonizing predator nets in 2011 and 2012.

Macroalgae on nets	*6/15/11*	*7/13/11*	*8/10/11*	*10/1/11*	*5/6/12*	*6/3/12*	*7/16/12*	*7/29/12*	*10/16/12*
Wet Weight (t)	17.52	10.33	9.08	3.33	28.95	19.57	12.85	10.91	2.11
Dry Weight (t)	2.14	1.26	1.11	0.41	3.53	2.39	1.57	1.33	0.26

Benthic and Epibenthic Invertebrates

Invertebrates on and around Chuckanut farm are largely small organisms of little economic value to the farm but of great value as food and prey for a wide range of ecologically and economically important resident and migratory fish and shellfish in Samish Bay. The following briefly summarizes results and interpretation of samples collected at the Chuckanut farm in 2011 and 2012. Detailed results of this sampling effort are reviewed and presented in Kralj (2017).

The densities and taxa richness of benthic fauna at off-farm reference sites were significantly greater than those of harvested sites. This difference between reference and farm sites is related, at least partially, to the somewhat lower elevation of reference sites and their close proximity to adjacent seagrass meadows. It was difficult to find a reference site that exactly replicated the farmed area because all the bare sand substrate on the farm was cultivated. There is a significant decrease in taxa richness after manual harvest but not after mechanical harvest (Kralj 2017). Taxa richness before manual harvest was consistently greater than after manual harvest but density or taxa richness was not different before and after mechanical harvest.

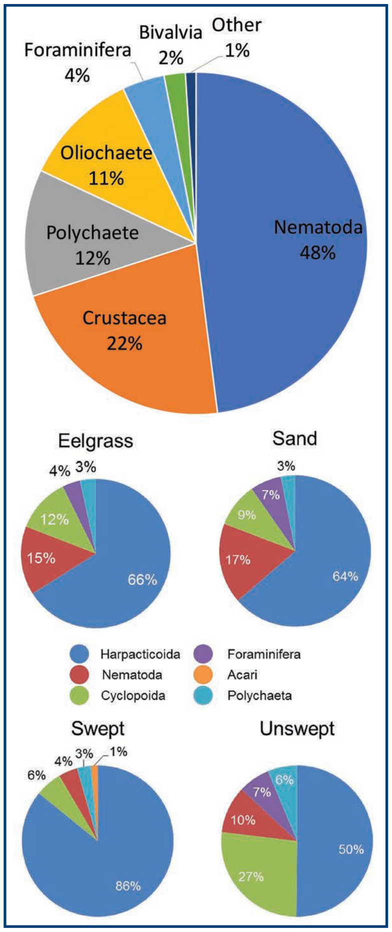
There were no significant differences between swept and non-swept plots for either density or taxa richness of epibenthic invertebrates. This is surprising considering the macroalgae cover on non-swept plots. Macroalgae density comparisons between net-covered plots and non-farmed seagrass and sand areas were inconsistent. In July 2011, swept and non-swept plots had significantly greater densities of epibenthic organisms compared to the seagrass substrate but in May 2012, seagrass had greater densities than all other substrate types.

A total of 172 and 125 unique taxa were identified in benthic and epibenthic samples respectively. Each taxon was assigned to a larger group to more broadly quantify proportions of each group in samples. In benthic samples, 99 percent of taxa were polychaetes, crustaceans, nematodes, bivalves or foraminifera (Fig. 10). Remaining organisms included insects, gastropods, echinoderms (*Holothuroidea* and *Ophiuroidea*), flatworms, phoronids, and an unknown non-annelid worm. About half of all animals in benthic samples were nematodes and about a quarter were worms (11 percent oligochaetes, 12 percent polychaetes).

(CONTINUED ON PAGE 54)

The five epibenthic groups that were most numerous in each substrate were selected and their relative proportions calculated (Fig. 10). These groups were the same at each substrate except the swept-net plots, which had acari or mites as one of the top five, rather than foraminifera. Harpacticoid copepods were the most abundant group, representing the majority of all taxa at each substrate. Harpacticoid and cyclopoid copepods appeared to be the most variable between substrates, ranging between 50-86 percent and 6-27 percent respectively while other groups were more consistent.

Farming activities such as net sweeping and harvesting had a minimal effect on species richness, composition or diversity. Salmonid prey species such as harpacticoid copepods were present before and after net sweeping. Benthic fauna displayed only slight differences after mechanical harvest and when compared with manual harvest.



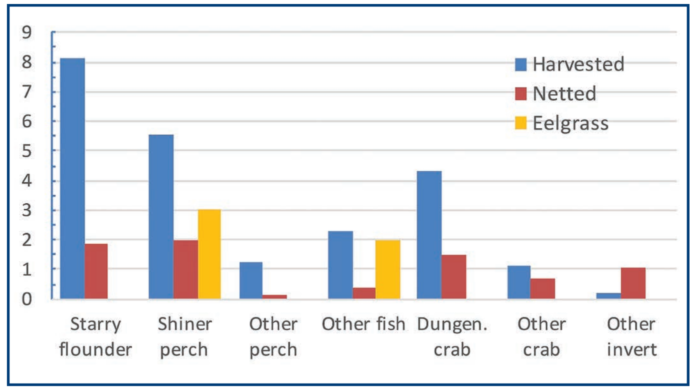


FIGURE 10 (LEFT). *Percent composition of benthic fauna (top) and percent composition of top five epibenthic taxa from each substrate type (bottom).*
FIGURE 11 (ABOVE). *Comparison of activity by fish and crustaceans expressed as an average count per minute observation period on harvested, netted, and eelgrass plots. Similar activity by a variety of bird species was observed on the exposed tracts immediately after harvest.*

Fish and Crabs — A Video Perspective

We gathered video imagery using tripod mounted digital point-of-view cameras between one day and one month after harvest or net sweeping. Video camera sampling was challenging in the dynamic and sometimes detritus-filled environment of Samish Bay; nevertheless, informative video imagery was obtained to characterize activities of large mobile macrofauna in unfarmed, netted areas, and recently harvested tracts at multiple dates from July through September 2011-13. Comparisons of activity by fish and crustaceans between habitat types were expressed as an average count and percentage of one or more animals per one hour observation period. During each sampling period four cameras were placed on two fixed platforms 15 cm and 45 cm off the bottom in oblique and vertical alignments.

Immediately following harvest, birds, usually gulls (*Larus* spp.) and great blue heron (*Ardea herodias*) were attracted to the exposed clam tracts. Within 30 minutes of tidal inundation, an increasing number of aquatic predators began to assemble, primarily dominated by starry flounder (*Platichthys stellatus*), shiner perch (*Cymatogaster aggregata*) and Dungeness crab (*Metacarcinus (Cancer) magister*). Other common taxa included *Cancer productus, Hemigrapsus oregonensis, Lumpenus sagitta, Pholis ornate, Leptocottus armatus* and other unidentified fish and invertebrates. Figure 11 illustrates these differences for the most abundant taxa seen on the site. Fish and crabs fed on small bivalves, polychaetes and other animals exposed by the action of the harvester. Feeding activity increased for the first 2-4 hours after harvest and declined within one day following harvest to levels seen on unharvested tracts.

In sum, disturbance of the harvest leads initially to increased foraging by birds during tidal exposure, followed by a pronounced and intense foraging response by fish and crabs attracted to the harvest site after tidal inundation. These foragers and predators targeted only larger organisms disturbed by harvesting. Density and species richness of smaller epibenthic and benthic organisms were not affected by harvesting.

Key Aspects of Farm Operations

Farming methods used at the Chuckanut Shellfish farm site are unique in several key ways. The site has a sandy substrate whereas most other farms in the region culture Manila clams in gravel, crushed shell, or mixed sand and gravel substrates. The farm is more intensively managed than traditional clam farms, with predator netting used throughout the production cycle, regular net maintenance to exclude predators, and monthly sweeping to reduce net fouling. Harvest is accomplished with a modified tulip bulb harvester during low tides when the farm is exposed, whereas the majority of Manila clams on the west coast of the US and Canada are currently harvested manually.

The Chuckanut growing grounds, however, present unique challenges for the farmer. It is in a relatively isolated location in the middle of Samish Bay and accessible only by boat, and then only during medium to high tidal ranges. The wide tide range (about 7 m) and seasonality of workable low tides means the time on the clam beds is limited to windows of 3-4 hours, and markedly constrained during winter months, when the best low tides occur late at night and sea conditions can be challenging.

Are Predator Nets Needed?

At Chuckanut, predator nets are deployed and remain in place for the whole culture period, and are then reused in the following cycle. What are the effects of this culture practice? These netted habitats contained greater densities and taxa richness of invertebrates compared to adjacent bare sand but lower mean richness than eelgrass covered sand sampled off the farm.

Predator netting causes sediment accumulation beneath nets (Kaiser *et al.* 1996, Spencer *et al.* 1997, Bendell-Young 2006, Dumbauld, Ruesink *et al.* 2009). Simenstad and Fresh (1995) found greater amounts of sediments in the <1-2mm grain size on gravel substrate under netting than on un-netted plots and suggested that nets may prevent resuspension. In similar studies (Spencer *et al*. 1996, 1997, 1998), organic enrichment and increased infauna densities occurred within net covered areas.

Kaiser *et al*. (1996) examined the effects of the growing phase of Manila clam cultivation on the intertidal benthic community at a commercial clam farm in southeast England. Predator netting, not the presence of clams, was the main cause of sediment deposition and community changes. In this case, although the density of benthic fauna was greater within netted plots than in control plots, there was no significant difference in species diversity between netted and control plots. The increased abundance of benthic fauna may have been related to predator exclusion and hydrographic changes associated with the netting, which increased food supply and the likelihood of larval settlement. As indicated by video observations taken immediately after harvest, there is a large pulse of prey availability after predator nets are removed and clams are harvested. Many prey items existing under netting were protected from predation for up to three years.

Luckenbach *et al*. (2016) reported decreases in the abundance and biomass of infauna (exclusive of cultured clams) on clam farms, including in harvested areas, relative to natural uncultivated areas. This was accompanied by substantial increases in epibenthic macroalgae, which in some cases supported increased epifaunal species richness and abundance relative to uncultivated areas. Habitat use by finfish, crustaceans and turtles was largely unaffected by the presence of clam farms.

These reports indicate site-specific conditions have a major influence on benthic and epibenthic usage and abundance. Using predator nets in Manila clam cultivation can result in lower or higher densities and taxa richness of invertebrates compared to control sites. However, sediment accumulation does not occur at the Chuckanut farm, at least from spring to fall. This is likely the result of high wind waves and moderate currents that act to sweep fines from nets and occasionally expose buried net margins. Munroe *et al.* (2007) also investigated possible sedimentation on netted clam ground and did not find increased sedimentation in clam farms in Baynes Sound, British Columbia.

Biofouling and Net Maintenance

Predator netting creates a hard substrate and becomes fouled with macroalgae and other flora and fauna in a community that is different from what might typically be found at that location. The production site was previously bare sand substrate with no structured habitat. Macroalgae production may be stimulated by the presence of clams (Bendell *et al*. 2014). Similar net fouling is associated with the use of predator nets at other farm locations (Spencer *et al*. 1997, Powers *et al*. 2007). Habitat provided largely by macroalgal growth on protective bottom mesh of clam leases supports elevated densities of mobile invertebrates and juvenile fishes similar to that of natural seagrass habitat, thereby representing a previously undocumented ecosystem benefit of bivalve aquaculture (Powers *et al*. 2007, Luckenbach *et al*. 2016). This ecological role for structural habitat rising above clam aquaculture growing beds is consistent with a broader recognition that artificial reefs, plastic seagrass, oyster shell mounds, and other emergent bottom structures provide significant habitat services.

Macroalgae fouling was routinely swept from the nets during spring and summer. If allowed to accumulate, net biofouling resulted in markedly increased juvenile clam mortalities. While most algae swept from nets drifted away with tidal flow, some algae remained in aisles between rows or prevented water from draining from the farm on ebb tides. However, algae removal by sweeping did not impact epibenthic organisms associated with the netting.

Do Nets Protect Clams?

There are contrasting views regarding the value of predator nets as a farm practice and their ecological impacts. Bendell (2015) concluded there was little evidence that nets protect farmed clams from predators mainly because they do not effectively exclude epibenthic predators such as crabs and fish (or are an attractant for these bivalve predators), poor husbandry of the nets results in gaps in the nets allowing for predation, and infaunal predation rates are high and infaunal predators can not be excluded (Cigarria and Fernandez 2000). A companion study (Whiteley and Bendell-Young 2007) conducted in the same region observed few effects of Manila clam culture on benthic bivalve diversity and abundance at multiple sites in Baynes and Barkley, and Desolation Sounds, British Columbia. Manila clam abundance and 25 other bivalve species densities were no different between sites in the mid-intertidal areas. Although farm sites had similar characteristics in species composition, differences between farm sites and references sites were small.

Munroe *et al*. (2015) provided data based on a review of more than 35 peer-reviewed articles and their own research that demonstrated the importance and efficacy of predator protection for clam farms in various locations around the world. A randomized side-by-side comparison of Manila clam survival and harvest between protected (netted) and unprotected control (non-netted) plots, showed clam survival and yield were consistently improved by using nets.

What Works for Chuckanut Shellfish?

Chuckanut Shellfish relies on several measures to improve clam survival. The netting is made of a relatively stiff and heavy polypropylene material and is not easily disturbed by waves or currents. Mechanical net deployment involves burying the margins of the net row and securing ends of netting material to exclude access for potential predators. Once the net is in place, clam seeding occurs during early tidal exposure when most potential predators are absent. This allows sufficient time for small seed clams to burrow beneath the surface covered by netting. Finally, netting is monitored throughout the culture cycle to ensure edges of the material are not exposed and to repair holes or damage to the net as a result of floating debris. These aspects of net type and installation and careful net husbandry are essential elements of the farm operation.

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On the Chuckanut Shellfish farm, predator nets are essential for survival of a marketable crop of Manila clams. Culture over multiple growing cycles has demonstrated that, without net protection or without timely net maintenance and oversight, the entire clam crop can be consumed by predaceous fish, crabs and diving ducks. Chuckanut Shellfish has observed 100 percent predation by crabs in 24 hours on year-old clams when nets have become dislodged during certain times of year. Video imagery clearly revealed the extent and intensity of predator activity on exposed and harvested tracts.

What are the Differences between Mechanical and Manual Harvest Effects?

There were few major or consistent differences in the benthic community before and after harvesting, no difference with mechanical harvest, and a modest decrease after manual harvest. The degree of sediment disturbance was similar for each method. In contrast with mechanical harvest methods such as suction harvest (Kaiser *et al*. 1996, Spencer *et al.* 1998), hydraulic dredging (Mercaldo-Allen *et al.* 2011), and "Rusca" harvest in Italy (Pravoni *et al.* 2004), the modified tulip-bulb harvester did not penetrate the substrate to a great depth, or remove or displace material, and therefore disturbed a relatively small volume of sediment.

Recently a research team in British Columbia, Canada employed a track driven walk-behind Manila clam harvester to compare mechanical with manual harvest. This harvester was similar to the machine employed by the Chuckanut farm in Washington. To determine the feasibility and potential benthic impacts of using this harvester, a comparative environmental assessment and operational performance of both mechanical and manual (i.e. hand rake) harvesting techniques were undertaken. In July 2008, assessments were conducted at three study sites in Baynes Sound, British Columbia. Each of the three sites contained a mechanical and manual harvest plot. No major differences were observed between the effects of each harvest method. Sulphide, redox potential and sedimentation was highly variable within treatment plots and transects, within all samples for each beach, and among samples for each beach. Despite the variability in results, sedimentation from mechanical and manual harvesting was negligible in comparison to the sediment flux occurring during natural processes (e.g., storm events) (Stirling 2011, Stirling and Cross 2013).

At first glance, the mechanized harvest method could be perceived as having a greater impact than manual harvest (Fig. 12). There are minimal physical differences between methods in harvest depth and redeposition of soils to the beach. The lack of increase or variations in sediment disruption could explain why this and earlier studies found no significant benthic fauna impacts between the two methods.

Mechanical vs Manual Harvest Costs

The main purpose of using mechanical tools to culture and harvest shellfish is to improve efficiencies and increase profitability. The current average cost to harvest Manila clams manually in Washington State is about \$0.45/lb. The cost estimate of harvesting Manila clams with a mechanical harvester is \$0.06/lb. Based on cost comparisons accounting for amortization of equipment and marginal costs, the harvest at Chuckanut Shellfish is more efficient (over 10 times faster) and cost-effective than manual harvesters using short-handled rakes. As of the date of this publication, Chuckanut Shellfish's modified tulip bulb harvester has dug one million pounds of clams over the past 16 years. Although designed for use in a tulip greenhouse, with routine cleaning, maintenance and occasional parts replacement, it works very well as a clam harvester.

FIGURE 12 (TOP AND BOTTOM). *Mechanical Manila clam harvester operating next to a traditional manual harvester in Samish Bay, Washington.*

The mechanical harvester performs the same work as eight manual clam diggers, with a comparable impact on harvest beds and in a shorter time. The relatively small size of Chuckanut Shellfish farm, coupled with a desire to minimize staffing requirements, and the ability of the grower to properly modify, maintain and operate culture and harvest equipment are key aspects of this farming practice. These are offset by the relatively high upfront costs of the mechanical equipment, the need for constant maintenance and repairs, and challenges of working within a narrow tidal window on a farm sometimes exposed to extreme weather conditions. Despite significant upfront costs, intensive production and harvesting methods have gained the attention of other clam growers and similar tools are now being deployed at several other locations in Washington State and British Columbia, Canada.

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Notes

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[1] SonTek Argonaut Acoustic Doppler Velocimeter

Unless otherwise noted, all photographs by Andrew Suhrbier, Dan Cheney or Bill Dewey.

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